

# **Collaborative Proposal: Earthquakes, fault rupture mechanics, and the link between the geometry of strike-slip fault intersections and earthquake rupture – a study of the Central California margin**

Hélène Carton, Suzanne Carbotte and Felix Waldhauser  
*Lamont Doherty Earth Observatory*

Steve Wesnousky and Graham Kent  
*University of Nevada, Reno*

Neal Driscoll  
*Scripps Institution of Oceanography*

## **Introduction**

The relationship between fault geometry and earthquake rupture remains limited by our inability to image faults in three dimensions. To date, our understanding has arisen, in large part, from the evaluation of surficial maps of faults and earthquake ruptures. The implementation of a 3D deep penetration multi-channel seismic reflection survey with the R/V *Langseth* in concert with a Phase 2 study involving high-resolution CHIRP and targeted coring holds the potential to image the geometry of an active fault at unprecedented resolution, along with placing detailed constraints on its paleoearthquake history. The effort will focus along the Hosgri Fault that strikes along the Central California coastal borderland and is one of the major strike-slip faults of California. The offshore location with ongoing accumulation of marine sediments, the interaction of tectonic slip and sediment accumulation, as well as the presence of geometrical steps and intersections of the fault with several other major faults make the Hosgri Fault an ideal target to extend the study of earthquake rupture and fault geometry to three dimensions. The results of this research when taken to fruition hold the potential to transform our present understanding of the interplay between fault geometry and earthquake behavior. A broader impact of the research will arise from characterizing the behavior of fault segments adjacent to one of our nation's major nuclear power plants. Finally, the three-dimensional picture of faults, micro-earthquake distribution, deeper-seated structure, and sedimentary accumulations that will arise and be delivered to the research community will facilitate new studies of the tectonic evolution of the Pacific/North America plate boundary. In the following science plan, we provide a brief description of the problems to be addressed, the methods that will be employed, and specifics of the research plan.

## **Scientific Rationale**

### *Fault Geometry and Earthquake Rupture*

Seismic slip on a crustal fault is controlled, among other factors, by the fault's geometric characteristics. Continental strike-slip fault systems present two main types of features influencing earthquake rupture: firstly, geometric irregularities and discontinuities such as releasing and restraining bends and step-overs [e.g. Wesnousky, 1988, 2006, 2008], which can act as barriers to rupture propagation depending on whether or not multiple fault strands observed at the surface connect to form a single fault surface at seismogenic depth; secondly, fault intersections (regions where a secondary fault branches off or joins a main fault), where an

earthquake rupture initiated on a fault can either continue on the same fault, branch on to an intersecting splay fault as occurred in the 2002 Denali earthquake [Scholz et al., 2009; Bhat et al., 2004], or continue on both strands. The underpinnings of seismic hazard analysis today [e.g., NSF's Southern California Earthquake Center; Field et al., 2009] are geologists' maps of active faults and decisions on the limits or endpoints of future earthquakes on those faults. Such decisions are based largely on the locations of geometrical discontinuities mapped along the faults [e.g., Field et al., 2009]. Yet, the faults and fault models are three-dimensional whereas our understanding of the role of fault geometry to rupture propagation has thus far been limited primarily to two-dimensional map views. To ultimately understand earthquake behavior and rupture segmentation of a given fault system or between neighboring - and hence potentially interacting - fault zones, it is key to assess how earthquake rupture patterns observed at the surface relate to the three-dimensional architecture of fault zones, as well as which part of the fault slips in earthquakes. The marine environment when coupled with seismic reflection techniques provides an unequaled ability to image the three-dimensional architecture of fault zones, extending to and below the base of the seismogenic zone and upwards to where the displaced surficial layers may be resolved at the decimeter-scale, and cored to reveal paleoearthquake records. The Hosgri Fault and adjacent faults offshore Central California provide an ideal locale to examine the relationship of fault junctions and discontinuities viewed on the surface to the underlying three-dimensional fault geometry in its entirety, and the controlling role these junctions and discontinuities play in limiting the extent of earthquake ruptures.

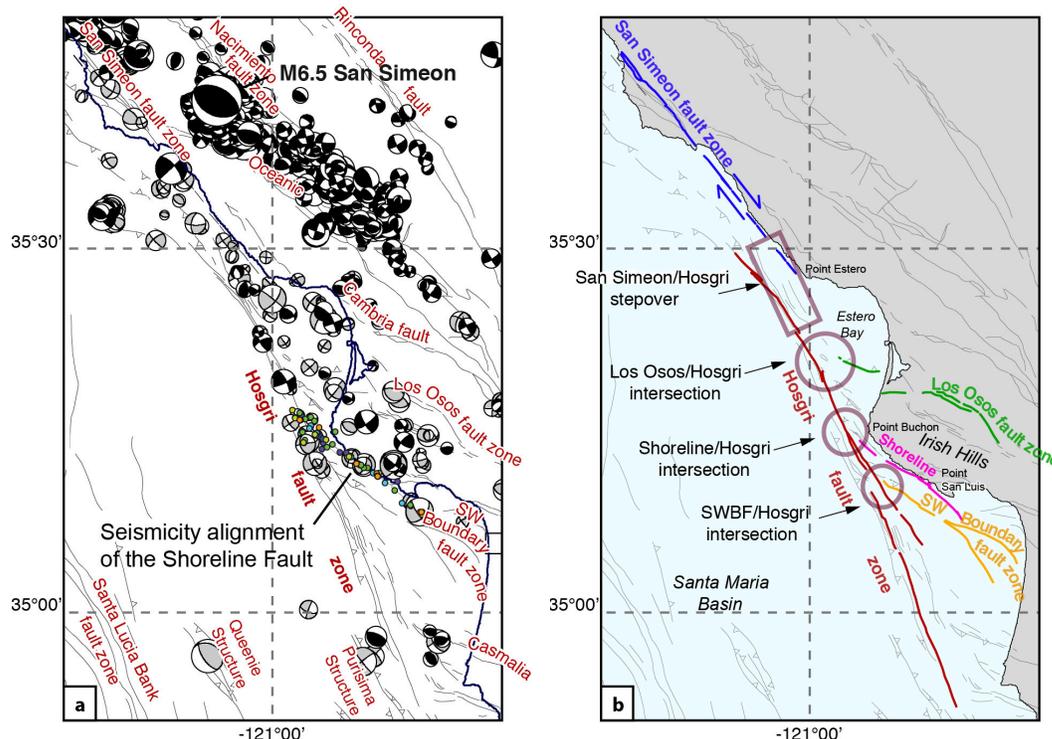


Figure 1: (a) Seismicity in the survey area for the period 1987-2008, from Hardebeck [2010]. Gray focal mechanisms are lower quality mechanisms but nonetheless adequately constrained. Faults (thin gray lines) are from Lettis et al. [2004]. (b) Major faults and associated geometrical steps and intersections along the Hosgri Fault System that are the main focus of this study.

### *The Hosgri Fault System*

The offshore Hosgri Fault System strikes northwestward along the central California Coast and adjacent to the Santa Maria Basin (**Figure 1**), ~100 km NW of the San Andreas Fault's "Big Bend". The Hosgri Fault accommodates ~1-3 mm/yr of right-lateral slip with a small contractional dip-slip component [Wolf and Wagner, 1970; Lettis et al., 1994; 2004; Hanson et al., 2004], and is marked by a zone of recent seismicity (**Figure 1a**). Slip is transferred to it from the San Simeon Fault farther north, across a possible releasing step-over located west of Point Estero [**Figure 1b**; Hanson et al., 2004]. The Shoreline Fault, recently identified from microseismicity and multibeam bathymetry data and located in the vicinity of Pacific Gas and Electric's Diablo Canyon Nuclear Power Plant (DCPP), is also right-lateral and intersects the Hosgri Fault at an acute angle southwest of Point Buchon [**Figure 1b**; Hardebeck et al., 2010; PG&E, 2009, 2011]. Its slip rate is presumably much lower than that of the Hosgri Fault [PG&E, 2009], and its paleoearthquake history is poorly constrained. The Los Osos Fault Zone, which bounds the uplifting Irish Hills in the north, likely accommodates thrust motion; its westward continuation meets the Hosgri Fault in Estero Bay (**Figure 1b**). The Southwestern Boundary Fault Zone (SWBF) defines the southern boundary of the Irish Hills and intersects the Hosgri Fault offshore Point San Luis (**Figure 1b**). The numerous discontinuities along the relatively short stretch of the Hosgri Fault System provide an ideal natural laboratory to examine the relationship of fault geometry and segmentation to earthquake rupture. Imaging the geometry of the releasing step-over near Point Estero and the intersection of the Hosgri with the Shoreline, Los Osos, and Southwestern Boundary Fault zones across a variety of scales as well as their paleoseismic history will be the overarching goal of this research.

### **Implementation**

We propose a research plan to conduct deep penetrating 3D seismic reflection profiling along the central California continental shelf region. Deep penetration seismic reflection will be accomplished during a ~50-day-long 3D MCS survey on the R/V *Langseth* that will image the Hosgri Fault and adjacent faults along an ~50-km long stretch of the margin. The proposed ship tracks are shown in **Figure 2** (acquisition is restricted to water depths > 25 meters) and are designed to develop a structural image through the seismogenic zone. Though 2D seismic images exist in the region from data acquired in the 1970's and 1980's, their depth extent is limited to 1-3 km below the seafloor and image quality is poor by modern standards. No multi-channel seismic (MCS) data were subsequently collected in this area using more modern systems.

The 3D velocity field derived from refraction measurements (from 6-km MCS streamer and ocean bottom instrument recordings), along with 3D pre-stack focusing/migration velocity analysis of the reflection data, will be used for proper 3D imaging. It will also provide the underlying model for precise, waveform-based relocation [using double-difference method; Waldhauser and Ellsworth, 2000] of 30 years of earthquakes recorded by the USGS in this region. Planned permanent OBS stations monitoring of the Hosgri/Shoreline fault intersection (yellow circles in **Figure 2**) will provide data that will allow illumination of fault zone structure by microseismicity as well as determination of fault kinematics at seismogenic depths in this target area.

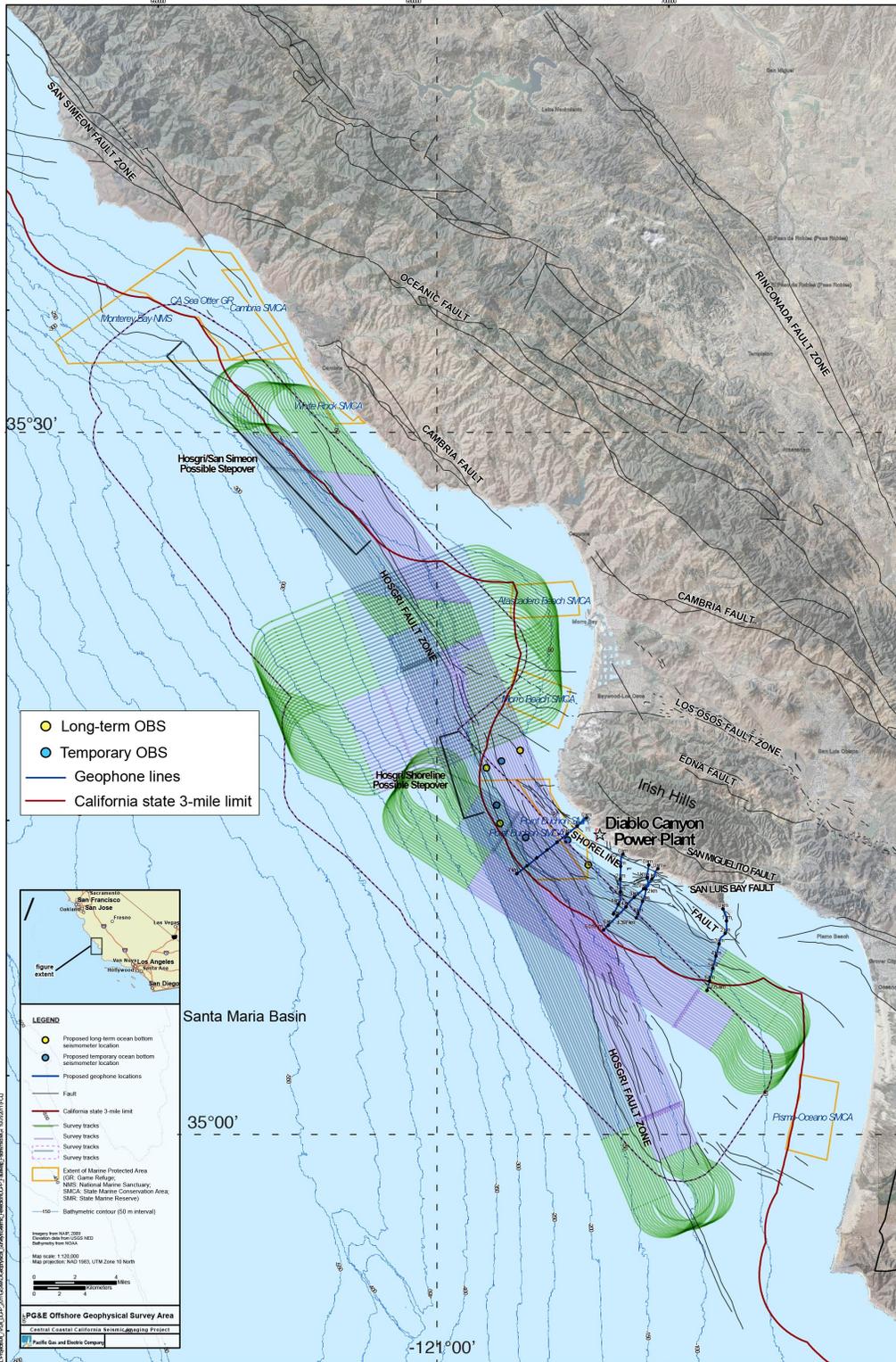


Figure 2: Location map of the proposed 3D MCS survey (same map boundaries as in Figure 1). Four main areas of 3D coverage are highlighted: Hosgri N, Hosgri S, Shoreline, Los Osos/Estero Bay. Areas of full-fold coverage with anticipated straight streamer are shown in blue and purple, turns and run-ins are shown in green (the Los Osos Fault continuation will be imaged using - full-fold - data from the run-in).

The expected resolution of a few tens of meters in both 3D seismic structure and earthquake locations along ~50 km of the Hosgri Fault zone and adjacent faults will be a first along any continental strike-slip system. The nested scales of imaging will describe the three-dimensional fault architecture from crustal-scale to the scale of the smallest geometric irregularities of the fault zones and the spatial dimension of individual earthquakes (for  $M > \sim 1$ ). The net sum of observations is needed to answer how fault geometry - as it is observed in three-dimensional seismic images and from present-day micro-earthquake activity - is related to the past occurrence of earthquakes. In so doing, it provides the opportunity to transform our understanding of the interplay between fault geometry in rupture propagation.

Pacific Gas and Electric (PG&E) would benefit from the proposed geophysical survey work by being able to better constrain the regional tectonic model of the area, and reduce uncertainty in their evaluation of seismic hazard at the Diablo Canyon Power Plant.

#### *Data acquisition, quality control, and dissemination*

It is anticipated that an industry vendor will carry out onboard preliminary processing and quality assurance / quality control (QA/QC) of the 3D MCS data. The approach ensures that the data quality is adequate and that the proposed targets are imaged properly. A similar 3 - 4 week 2D MCS survey with the *R/V Langseth*, and possibly incorporating the same vendor for onboard processing, will be taking place for the SONGS project about 200 km to the south immediately before or after this project. The commercial processing equipment could be set up only once aboard *R/V Langseth* and would be used during the two successive surveys – achieving a greater efficiency. The survey will also acquire high-quality multibeam bathymetry data, seafloor imagery, gravity and magnetics, as well as hull-mounted CHIRP data, all of which will provide complementary constraints to the 3D MCS dataset.

All data acquired by *R/V Langseth* during this project will be accessible to the broader scientific community. Underway data will be transmitted to open archives of the NDCs through the Rolling Deck to Repository program ([www.rvdata.us](http://www.rvdata.us)). Quality control of the MCS data will continue post-cruise for a period of 6–12 months. Once vetted, all raw data will be submitted to the NSF-supported open access Academic Seismic Portal at LDEO (<http://www.marine-geo.org/seismic>) and processed data will be submitted to the partner Academic Seismic Portal at UTIG (<http://www.ig.utexas.edu/sdc>).

As part of this project the PIs will also have access to all data PG&E has recently collected within the region including the P-Cable, Sparker and existing CHIRP data, onshore Vibroseis survey data, as well as their compilation of legacy MCS data.

#### **Future work (“Phase 2”)**

Data collected during this 3D deep seismic program will provide a sound basis for future research of high-resolution CHIRP seismic reflection profiling and age dating at the step-overs and fault junctions shown in **Figure 1b** to establish a chronostratigraphy for fault recurrence and the most recent event (MRE). Such a nested approach using CHIRP and 3D MCS datasets will identify sag basins along the intersecting faults that contain a stratigraphic record of deformation and segment interaction. These sites will then be the focus of a large-diameter piston-coring program to sample organic matter for radiocarbon dating to yield age constraints for fault offsets imaged in the seismic data. A paleoseismic history for the fault segments will be constructed

from these age-offset relationships. The US Geological Survey has also expressed interest in participating in these studies once sites have been identified.

## **Summary and Additional Benefits**

The Central California coast and Hosgri Fault System provides a natural laboratory to examine in unprecedented detail a fundamental problem in earthquake rupture mechanics, the role of three-dimensional fault geometry in limiting the extent of earthquake ruptures. The problem by itself is of intrinsic and fundamental importance to the community of scientists attempting to understand earthquake rupture mechanics. Understanding the problem also holds significant societal benefit. Estimating the limits of future earthquake ruptures is becoming increasingly important as seismic hazard maps are based on geologists' maps of active faults and, locally, the Hosgri Fault strikes adjacent to one of California's major nuclear power plants.

### *Education*

The survey will be carried out close to shore and several supply vessels will be available. Personnel transfer should be easy to arrange, and stays onboard as short as 1 week are envisioned. To take advantage of this flexibility, and recognizing the opportunity for developing a rich educational component, we will invite graduate students and post-docs at our own and other institutions to participate in this cruise. We expect to advertise this opportunity via the UNOLS office and the MLSOC, as has been done for the Holbrook/Kent Cascadia cruise this summer. We also will anticipate hosting a three-week course in marine reflection seismology on the ship, which would provide formal training to students in addition to their day-to-day watchstanding duties.

### *Implications of data dissemination for studies of margin evolution*

The tectonic evolution of the continental margin is of great interest to a large group of earth scientists spanning the disciplines of geology, seismology, and geophysics and is a fundamental tenet of the NSF GeoPRISMS program. The state-of-the-art nested geophysical data collected along this section of the North America West coast margin will provide new insights into margin reorganization and evolution. The observations, will in turn, lead to an improved understanding of Mesozoic to Paleogene subduction along the margin, the tectonics of oblique extension during the earliest Miocene, processes of transtensional deformation during the Miocene, and the transition to primarily right-lateral strike-slip tectonics from Plio-Pleistocene to Present.

## **Project personnel and responsibilities**

This 3-year collaborative project will be led by scientists at Lamont-Doherty Earth Observatory (LDEO - S. Carbotte, H. Carton, F. Waldhauser), and the University of Nevada, Reno (UNR - S. Wesnouky, G. Kent), and Scripps Institution of Oceanography (SIO - N. Driscoll). Responsibilities are outlined below.

Through their involvement in the SONGS project, N. Driscoll and G. Kent are ideally positioned to ensure synergy between these two projects from cruise planning stage to data processing and interpretation. They will perform this liaison role throughout. H. Carton, who has worked on survey design from November, 2011 to March 2012 with LDEO's Office of Marine Operations and PG&E, and S. Carbotte, will be primarily responsible for cruise preparation. H. Carton and

S. Carbotte will serve as Chief Scientist for the planned two legs of the cruise. It is anticipated that onshore 3D MCS data processing will be performed commercially by GeoTrace (for QA purposes shipboard and onshore processing should be conducted by the same contractor). The science team will collaborate with PG&E on data processing, to ensure targets are well imaged. Processed data will be open source. LDEO (lead institution - S. Carbotte, H. Carton, F. Waldhauser) and UNR (S. Wesnousky) will be responsible for post-cruise science, including data processing/analysis other than that done commercially, and interpretation. Together they will supervise students and/or post-docs. Specifically, H. Carton will be responsible for the refraction analysis and imaging. F. Waldhauser will be responsible for the micro-seismicity relocation. S. Carbotte and S. Wesnousky will be responsible for the 3D interpretation, respectively focusing on segmentation and fault mechanics aspects, and will work on margin-scale implications. All scientists will work together on integrating science results.

## References

- Scholz, C. H., Ando, R. and Shaw, B. E. (2010), The mechanics of first order splay faulting: the strike-slip case, *Journal of Structural Geology*, 32, 118-26.
- Bhat, H.S., R. Dmowska, J.R. Rice, and N. Kame (2004). Dynamic slip transfer from the Denali to Totschunda Faults, Alaska: testing theory for fault branching, *Bull. Seismol. Soc. Am.*, 94(6B), S202-S213.
- Field, E. H., Dawson, T. E., Felzer, K. R. and 8 more (2009), Uniform California earthquake rupture forecast (UCERF 2), *Bulletin of the Seismological Society of America*, 99, 2053-2107.
- Hanson, K.L., Lettis, W.R., McLaren, M.K., Savage, W.U., and N.T. Hall (2004). Style and Rate of Quaternary Deformation of the Hosgri Fault Zone, Offshore South-Central California, Chapter BB of *Evolution of Sedimentary Basins/Offshore Oil and Gas Investigations-Santa Maria Province*, Keller, MA. (editor), USGS Bulletin 1995-BB, 36 pp.
- Hardebeck, J.L. (2010). Seismotectonics and fault structure of the California Central Coast, *Bull. Seismol. Soc. Am.*, Vol. 100, No. 3, doi 10.1785/0120090307.
- Lettis, W.R., Kelson, K.I., Wesling, J.R., Angell, M., Hanson, K.L., and Hall, N.T. (1994). Quaternary deformation of the San Luis Range, San Luis Obispo County, California, in Alterman, I.B., McMullen, R.B., Cluff, L.S., and Slemmons, D.B., eds., *Seismotectonics of the central California Coast Ranges: Geological Society of America Special Paper 292*, p. 111-132.
- Lettis, W.R., Hanson, K.L., Unruh, J.R., McLaren, M., and W.U. Savage, 2004, Quaternary tectonic setting of south-central California, Chapter AA of *Evolution of Sedimentary Basins/Offshore Oil and Gas Investigations-Santa Maria Province*, Keller, MA. (editor), USGS Bulletin 1995-AA, 24 pp.
- Waldhauser, F., and W. L. Ellsworth (2000). A double-difference earthquake location algorithm; method and application to the northern Hayward fault, California, *Bull. Seismol. Soc. Am.* 90, 1353–1368.
- Wesnousky, S.G. (1988), Seismological and Structural Evolution of Strike-Slip Faults, *Nature*, 335, 340-343.
- Wesnousky, S. G. (2006), Predicting the endpoints of earthquake ruptures, *Nature*, 444, 358-360, doi:10.1038/nature0525)

- Wesnousky, S. G., (2008), Displacement and geometrical characteristics of earthquake surface ruptures: Issues and implications for seismic hazard analysis and the earthquake rupture process, *Bulletin of the Seismological Society of America*, 98, 4, 1609-1632.
- Wolf, S.C., and Wagner, H.C. (1970). Preliminary reconnaissance marine geology of area between Santa Lucia escarpment and Point Buchon, California: unpub. U. S. Geological Survey administrative report, 5 p.